Computers & Operations Research 78 (2017) 1–14

Contents lists available at ScienceDirect

Computers & Operations Research

journal homepage: www.elsevier.com/locate/caor

An adaptive neighborhood search metaheuristic for the integrated railway rapid transit network design and line planning problem

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ARTICLE INFO

Article history:
Received 10 September 2015
Received in revised form
11 May 2016
Accepted 19 August 2016
Available online 21 August 2016

Keywords:
Railway rapid transit
Network design
Line planning
Adaptive large neighborhood search

ABSTRACT

We model and solve the Railway Rapid Transit Network Design and Line Planning (RRTNDLP) problem, which integrates the two first stages in the Railway Planning Process. The model incorporates costs relative to the network construction, fleet acquisition, train operation, rolling stock and personnel management. This implies decisions on line frequencies and train capacities since some costs depend on line operation. We assume the existence of an alternative transportation system (e.g. private car, bus, bicycle) competing with the railway system for each origin–destination pair. Passengers choose their transportation mode according to the best travel times. Since the problem is computationally intractable for realistic size instances, we develop an Adaptive Large Neighborhood Search (ALNS) algorithm, which can simultaneously handle the network design and line planning problems considering also rolling stock and personnel planning aspects. The ALNS performance is compared with state-of-the-art commercial solvers on a small-size artificial instance. In a second stream of experiments, the ALNS is used to design a railway rapid transit network in the city of Seville.

1. Introduction

Network design is the first stage of the railway planning process [14,24]. The network design problem has been traditionally modeled and solved considering a set of candidates alignments and modeling the selection of a subset of those alignments in order to maximize demand coverage [37,31], maximize social welfare [42], minimize the total cost [18], the transfers number between lines [23,45] or maximize total profit [32]. The first studies focused on the design of a single rapid transit alignment. For instance, Gendreau et al. [21] described the main criteria used to design rapid transit alignments, Dufourd et al. [17] proposed a tabu search algorithm for this problem, Bruno et al. [7] proposed a bicriterion model for the location of a rapid transit line minimizing construction cost and passenger travel time, Bruno et al. [6] developed a two-phase heuristic for the problem of designing an alignment in a urban context maximizing the population coverage, Laporte et al. [30] presented a heuristic for the construction of a rapid transit alignment maximizing trip coverage, and Laporte et al. [29] addressed the problem of locating a metro line maintaining a minimum distance between the alignment to be designed and historical buildings, by computing shortest paths on a Voronoi diagram. Most of the papers have been devoted to the simultaneous design of several alignments. Among them, Blanco et al. [2] proposed a model and a heuristic for the problem of expanding the infrastructure of railway networks. García-Archilla et al. [19] used a Greedy Randomized Adaptive Search Procedure (GRASP) for solving the infrastructure railway network design problem as well as its robust version. Using simulated annealing (SA), Kermanshahi et al. [26] solved the rapid transit network design problem by maximizing the trip coverage. The line planning problem (the second stage in the railway planning process) focuses on determining a subset of all possible paths linking demand origins and destinations (using the infrastructure network obtained in the Network Design stage) and providing the sufficient capacity to meet the passenger demand, see [34] for a recent survey. Supposing train capacity is known, the problem consists of defining several paths called lines, corresponding to a convenient succession of stations and edges linking a subset of demand origins and destinations, and determining their services frequency. The Line Planning problem has been addressed by several authors. Bussieck et al. [8] and Claessens et al. [12] both proposed branch-and-cut algorithms to select lines from a previously generated set of candidate lines (line pool). The line selection is done after a demand-split procedure (a distribution of passengers on paths in

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http://dx.doi.org/10.1016/j.cor.2016.08.008
0305-0548/

the transportation network) is performed as a preprocessing step before the lines are known. Bussieck et al. [9] extended this work by designing a procedure that computes lower bounds from different linearizations in order to assess the quality of solutions. The integer linear programs involved are strengthened by means of problem-specific valid inequalities. Similarly, Goossens et al. [22] addressed the line planning problem minimizing total costs. Their model is solved by means of a branch-and-cut algorithm, for which, authors develop several valid inequalities and reduction methods. In this paper, we consider the problem of simultaneously designing the infrastructure of a railway rapid transit network (RRTN) and the set of lines [36,33], called Railway Rapid Transit Network Design and Line Planning (RRTNDLP), in order to maximize the total profit, integrating the two first stages of the Railway Planning Process taking into account aspects related to rolling stock and personnel costs. To define the profit, we use real-based costs and consider the investment planning horizon by incorporating a discount factor. Since operational costs are dependent on frequencies and rolling stock, optimal frequency and train capacity should be considered when a global characterization of total costs is pursued. So, given an average travel demand, we consider variable operation costs, rolling stock and crew costs with the goal of designing the best physical network and the most convenient line design. This way, costs include fixed and variable operation costs due to infrastructure management and investment, and costs due to train acquisition and operation [12,22]. Note that with respect to traditional approaches, an a priori line pool is not needed. In fact, our approach can be viewed as "constructive" as in [28] or [35]. Moreover, we also consider the determination of the optimal frequency and train capacity for each line.

A similar problem was treated in [11], where the authors proposed a general model that was approximately solved on small instances following a parametric analysis and a branch-and-bound procedure. The model proposed in this paper differs significantly from that of [11] with respect to the variables that define the flow of passengers. In the former, the flows are measured as fractions of the demand corresponding to each origin-destination (OD) pair whereas in the present formulation, binary variables are considered in order to determine the use of links for each OD pair. The previous work modeled the best favorable situation from the point of view of the service provider, allowing the division of flows between the different possible routes for each OD pair. In contrast, the proposed formulation considers the worse situation for the service provider's point of view, where passengers want to reach their destination using the fastest route.

Due the complexity of the problem, a more efficient approach is needed in order to deal with real-size network instances. Hence we propose an adaptive large neighborhood search (ALNS) metaheuristic which provides a powerful framework capable of simultaneously handling network design and line planning. Thus, as main contributions, this paper presents a new formulation of the RRTNDLP problem and a powerful ALNS metaheuristic to solve real-size network instances.

The remainder of this paper is structured as follows. The next section introduces a non-linear mixed integer model that simultaneously determines the most convenient network topology and the most appropriate set of lines, considering variable line capacity and frequencies. Section 3 presents an ALNS procedure designed to manage real-size instances of the RRTNDLP problem. Section 4 illustrates the computational difficulty of the problem considering different scenarios. We apply state-of-the-art commercial solvers on several instances and we report computational results. The ALNS is then used with the goal of solving efficiently the set of testing scenarios and comparing results with respect to the exact approaches. A real-size instance of the RRTNDLP for the city of Seville is finally solved using the ALNS algorithm. The last section provides some conclusions and avenues for further research.

2. Mathematical model

Consider a set $N = \{1, \dots, n\}$ of potential nodes for locating stations and a set of arcs $A \subseteq N \times N$ representing potential connections between nodes. Both sets define the underlying or potential graph used as a basis for the building of the railway rapid transit network. From the arc set, we define the edge set $E = \{\{i, j\}: i, j \in N,\ i < j, (i, j) \text{ or } (j, i) \in A\}$ and, for each node i, the set $N(i) = \{j \in N: \{i, j\} \in E\}$ of adjacent nodes. Thus, the underlying network can be topologically described as a graph $G_E = G(N, E)$. We also consider an alternative mode (private car, bus, etc.), competing with the railway rapid transit system, whose network is represented as an undirected graph $G_{E'} = G(N, E')$. As is usual in the network design, there exists an upper bound C_{max} on the total construction of the RRTN.

Let $W = \{w_1, \dots, w_{|W|}\} \subseteq N \times N$ be the set of ordered OD pairs $w = (o^w, d^w)$, where o^w represents the origin and d^w is the destination of pair w respectively. Without loss of generality, we assume that all trips occur between stations of the system, that is, the centroid of each transportation area is assumed to be a potential station. We know the expected number of passengers g_w associated with each OD pair $w \in W$, as well as the corresponding travel time u_w^{ALT} of pair w using the alternative mode. In order to compute the travel time associated to each OD pair using the railway rapid transit system, two parameters are needed: d_{ij}, which represents the length of edge $\{i, j\}$, and λ, denoting the average speed of trains (design speed or commercial speed) measured in km/h. As in [20], the transfer time is the sum of two terms: the time spent between platforms uc_i and the average waiting time for taking the next train of the line to transfer. The last term can be calculated as the average headway of the line to transfer.

The two main variables to be determined for each line are the headway between consecutive trains and the capacity of each train. The last defined term is defined as the product of the capacity Θ of a carriage (measured in number of passengers seating and standing), and the number of train carriages (we assume all trains of a line operate at the same capacity). In order to obtain applicable results, we work with a discrete set $\mathcal{H}$ of headways. We consider a parameter γ representing the line multiplicity, i.e., the maximum number of lines that can circulate on any edge of the network. This is a topological constraint frequently used in order not to oversaturate some open tracks, which would result in excessively long headways (low frequencies). Also, a lower bound on the number of carriages δ^{min} of each train is given. We denote each line by the index $\ell \in \mathcal{L}$, where $\mathcal{L}$ is a set used to simply enumerate the possible lines and $|\mathcal{L}| = \mathcal{L}^{\max}$. As previously mentioned, no a priori line pool is defined, and since a constructive approach is followed, a lower and an upper bound, N_{min} and N_{max}, on the number of stations of each line are considered [10].

As already mentioned, the objective function is the profit z_{NET}, expressed as the difference between the revenue z_{REV} and the system cost z_{SC}. To define the revenue, we consider two parameters: a passenger fare τ and a passenger subsidy η [5,15]. The system cost z_{SC} is composed of three main terms as follows (see [11]). The first one corresponds to the construction cost z_{BC} for stations and edges. This term is described by means of two parameters: c_{ij} and c_i, denoting the cost of building a link on edge $\{i, j\}$ or a station i, respectively. The second term is the operating cost z_{OC}, which includes fixed and variable costs. The fixed cost is related to maintenance and overheads of rails ORC_{ij} and stations